Connecting the Great Lakes in MOM6

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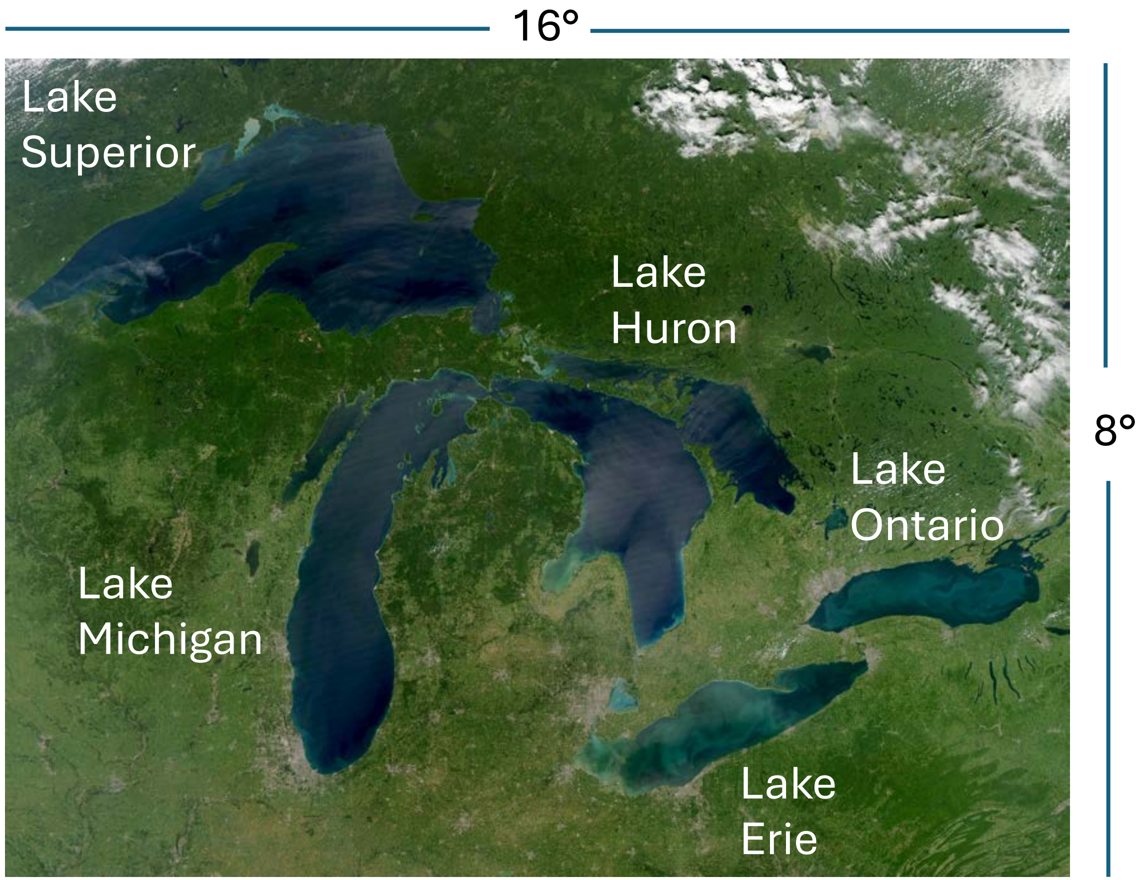
Outline

- Background
- Sub-grid scale topography
- Prototype of hydraulic control representation

The Laurentian Great Lakes

- Total surface area: 244,000 km^2
- As deep as 400 m (Lake Superior)
- 21% of world's surface freshwater
- 3500 species of plants and animals
- 34 million population
- Vital economic resource



From NASA's Aqua satellite in August 2010

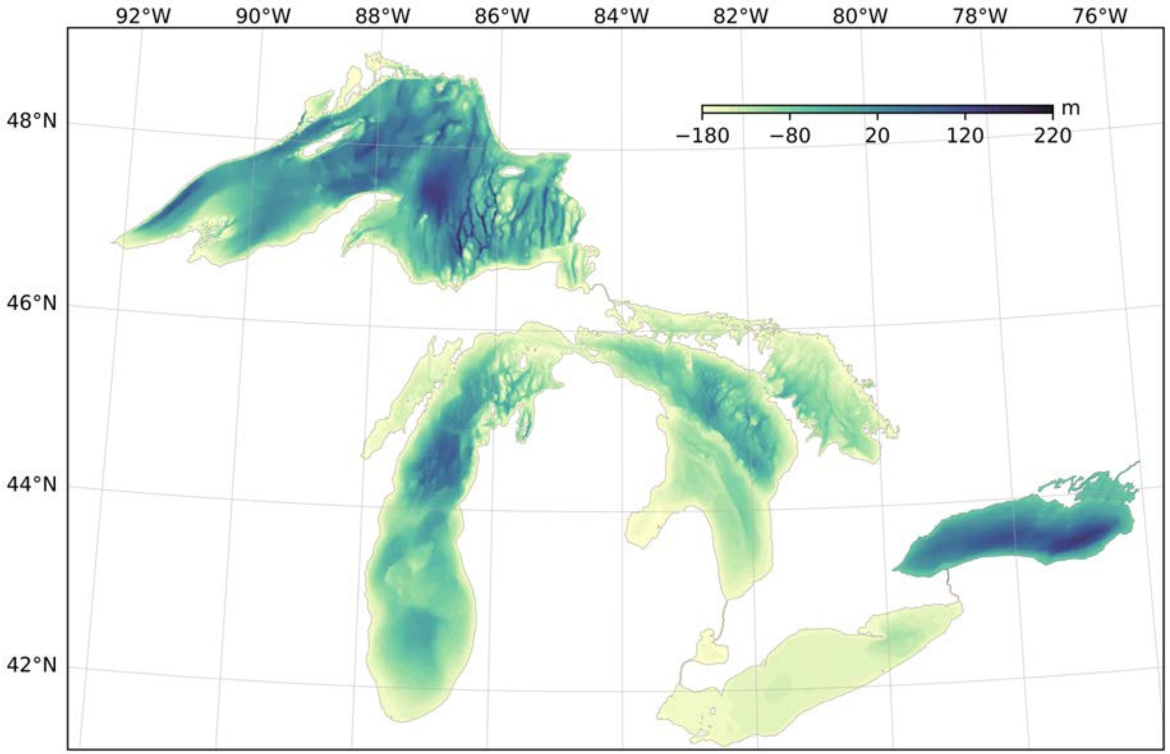
Why do we (ocean modelers) care?

- Physical scales and features are not that different.
  - Coriolis
  - Thermal inertia
  - Bathymetry, mixing, convection, surface waves, lake ice and etc..

- Regional climate driver
  - Lake circulations
  - Biases in climate models: missing or insufficient representation of the Great Lakes
    - As land
    - As a part of land model (single columns)
    - As ocean (a couple of grids and no circulation)

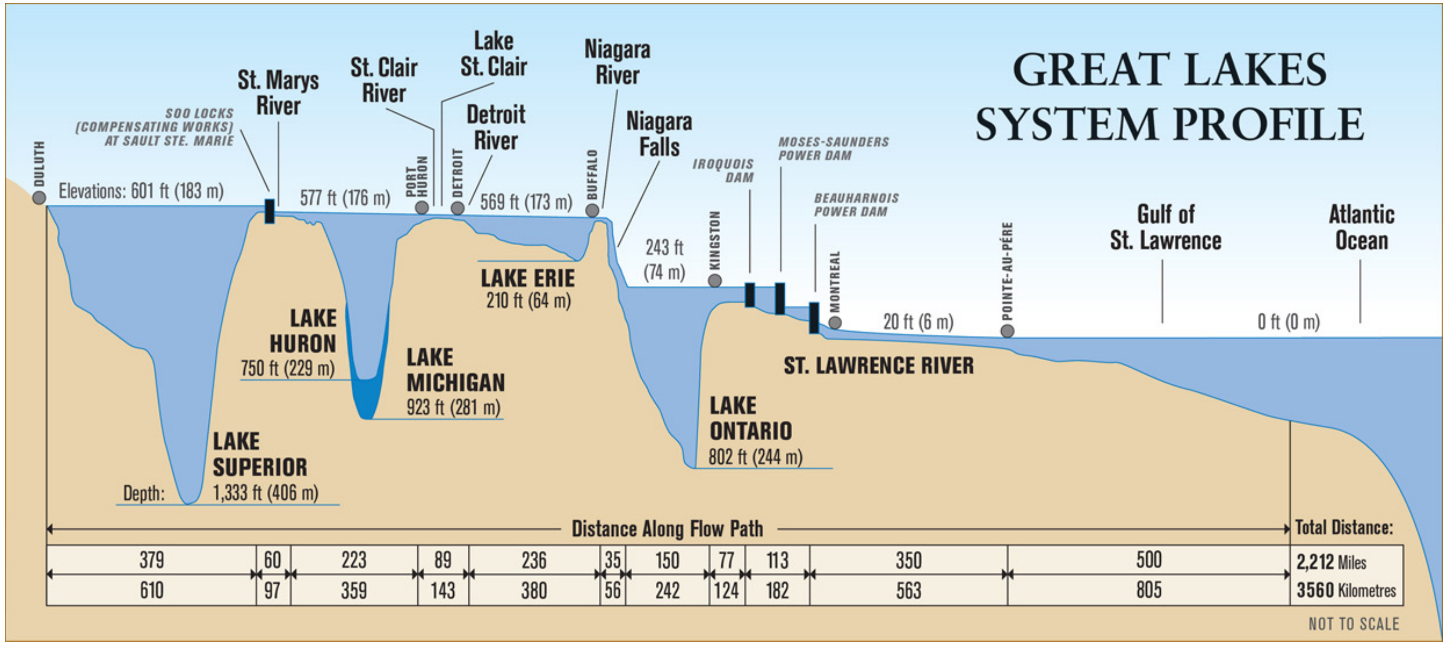
Building a Great Lakes model with MOM6

- Objective: MOM6 for the **interconnected** Great Lakes
  - A regional model: 1 km resolution
  - An interactive Great Lakes component in global ocean model and climate/earth system models: much coarser resolution
- Previous works: regional model
  - Separate lakes with closed basins
  - Need to specify zero mass flux at both lateral and surface boundaries for long term simulation



Depths of the Great Lakes on a 1-km model grid, referenced to sea level. The Lakes are connected by 1-km-wide artificial rivers.

Challenges in connecting the Great Lakes



- Mean water levels in the Great Lakes system is not uniform.
- (Narrow) rivers connect the individual lakes as well as the Great Lakes and the Atlantic Ocean.
- Water level can change rapidly along the waterways.
  - St. Marys Rapids
  - Niagara Falls
  - St. Lawrence Rapids
- Man-made structures (locks, canals, weirs, dams, and etc.) and international laws

Sub-grid scale topography

- Discretized model grid is always too coarse for real world topography/bathymetry.
  - Model topography has limited degrees of freedom, constrained by resolution: one single depth per grid cell.
- Cell edge depth is (often implicitly) derived from cell center depth.
  - No restriction on cell wall connectivity from topography
  - Narrow channels cannot be realistically represented.
- Cell center depth is an average of the cell.
  - Misplaced water masses
  - Pressure gradient
- Porous topography (Adcroft 2013)
  - Use simple profiles to represent the geometric effect of sub-grid scale topography
  - Weight functions of depth for connectivity and capacity

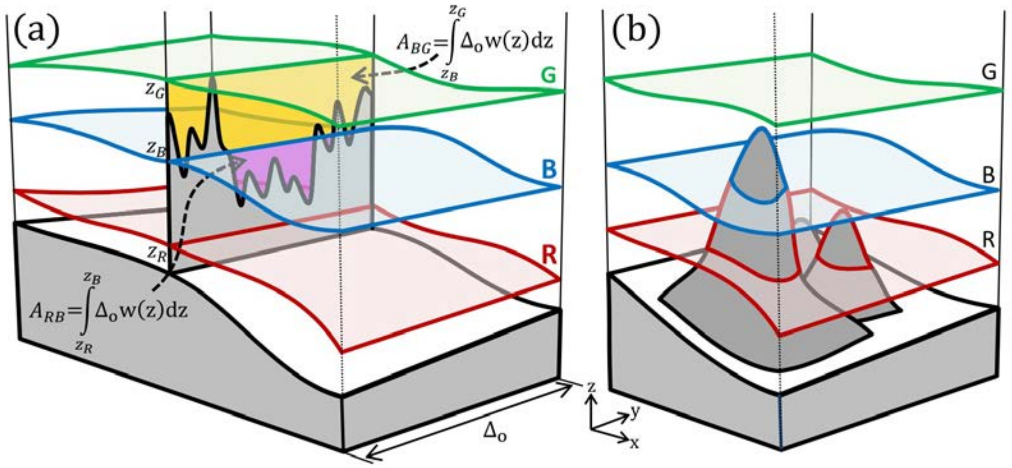


Illustration of layers intersecting two types of sub-grid scale feature: a porous barrier and a porous medium, from Adcroft (2013).

Constructing a weight function

Conditions:

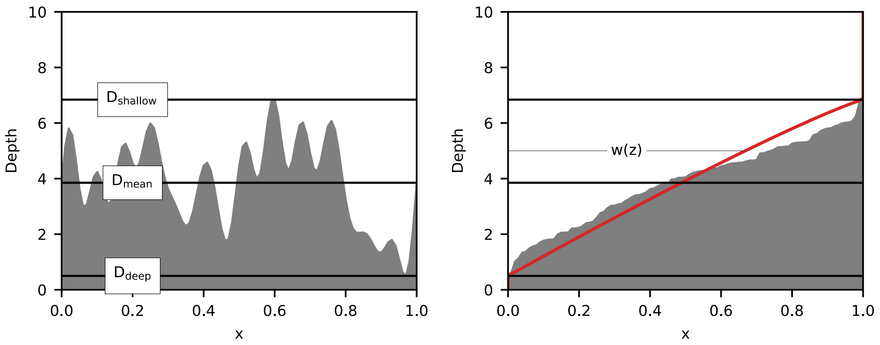
- Weight function is zero below the deepest depth, one above the shallowest depth, and smaller than one in between.

$$w(z) = \begin{cases} 0, & z < D_{deep} \\ \psi(z), & D_{deep} \leq z \leq D_{shallow} \\ 1, & z > D_{shallow} \end{cases}$$

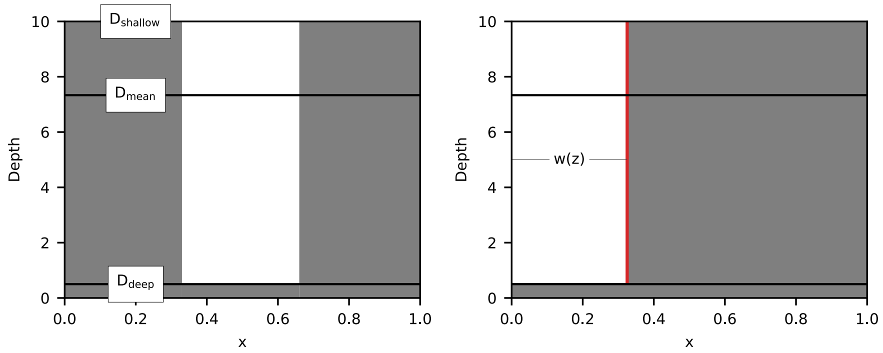
- Integral between D_{deep} and $D_{shallow}$ should equal D_{mean}.

$$\int_{D_{deep}}^{D_{shallow}} \psi(z)dz = D_{mean}$$

  - Mean face area at the wall -> connectivity
  - Mean depth at the cell center -> capacity



$\psi(z)$: a three-parameter fit to a monomial of depth.
[Appendix A, Adcroft (2013)]



(A special case) $\psi(z)$ is constant, independent of depth.
Used in a number of models at well-known narrow channels.

Adjusting cell edges: porous barriers

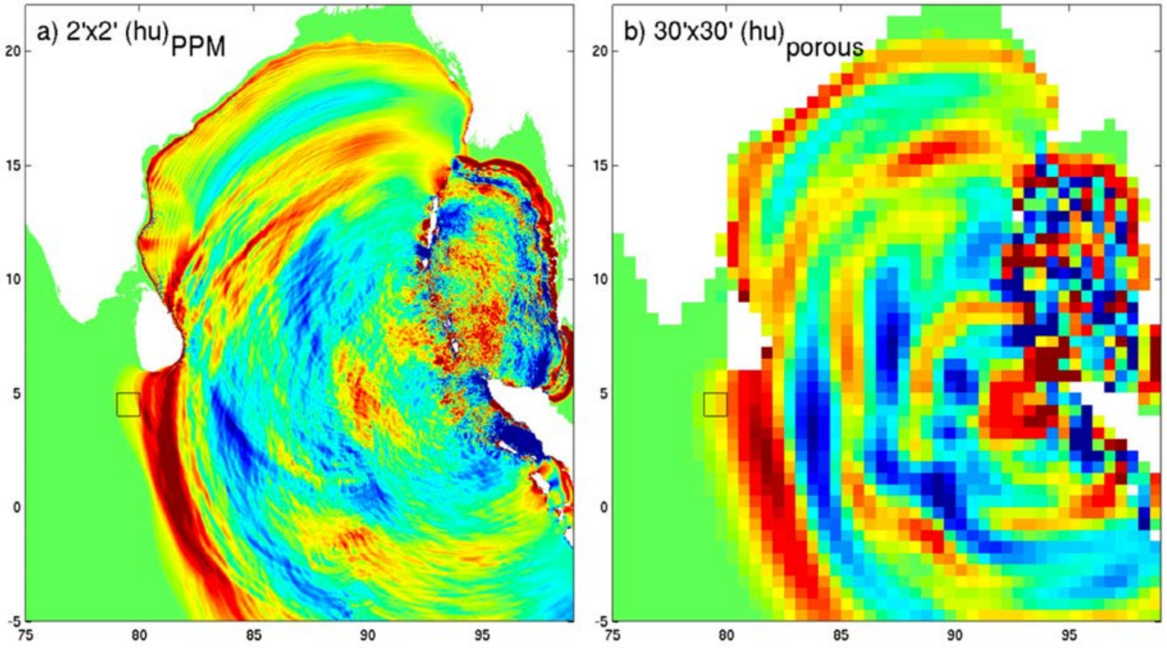
- Implementation: modify volume fluxes in continuity equation
  - $h^{(n+1)} = h^{(n)} - \left[\delta_x\left(\alpha_x^{(n)} F_x^{(n)}\right) + \delta_y\left(\alpha_y^{(n)} F_y^{(n)}\right)\right] \cdot \Delta t/(\Delta x \Delta y)$

$$\alpha^{(n)} = \frac{\int_{\eta_b^{(n)}}^{\eta_t^{(n)}} w(z)dz}{\eta_t^{(n)} - \eta_b^{(n)}}$$

- Transport is always reduced [$\alpha^{(n)} \leq 1$].
- For barotropic runs, α may only need to be calculated once.
- For baroclinic runs, α has a larger effect on deeper and denser flow transports.

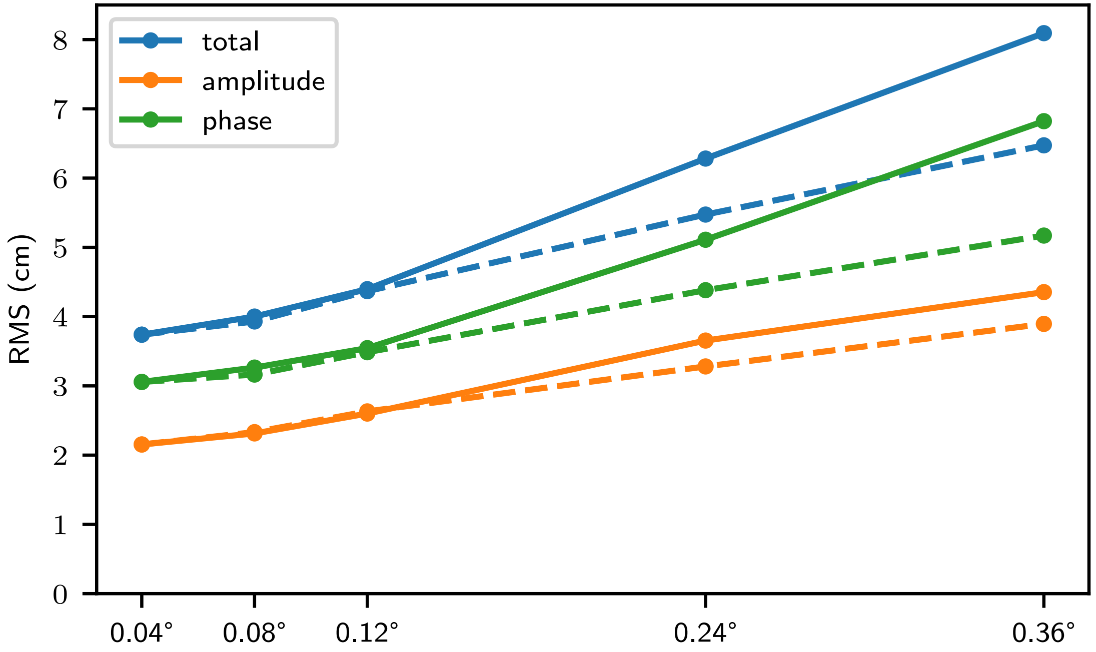
Porous barriers applications

Sumatra-Andaman Tsunami (Adcroft (2013))



- Porous barriers produce similar arrival time in low resolution compared with high resolution.
- Make topography less sensitive to resolution

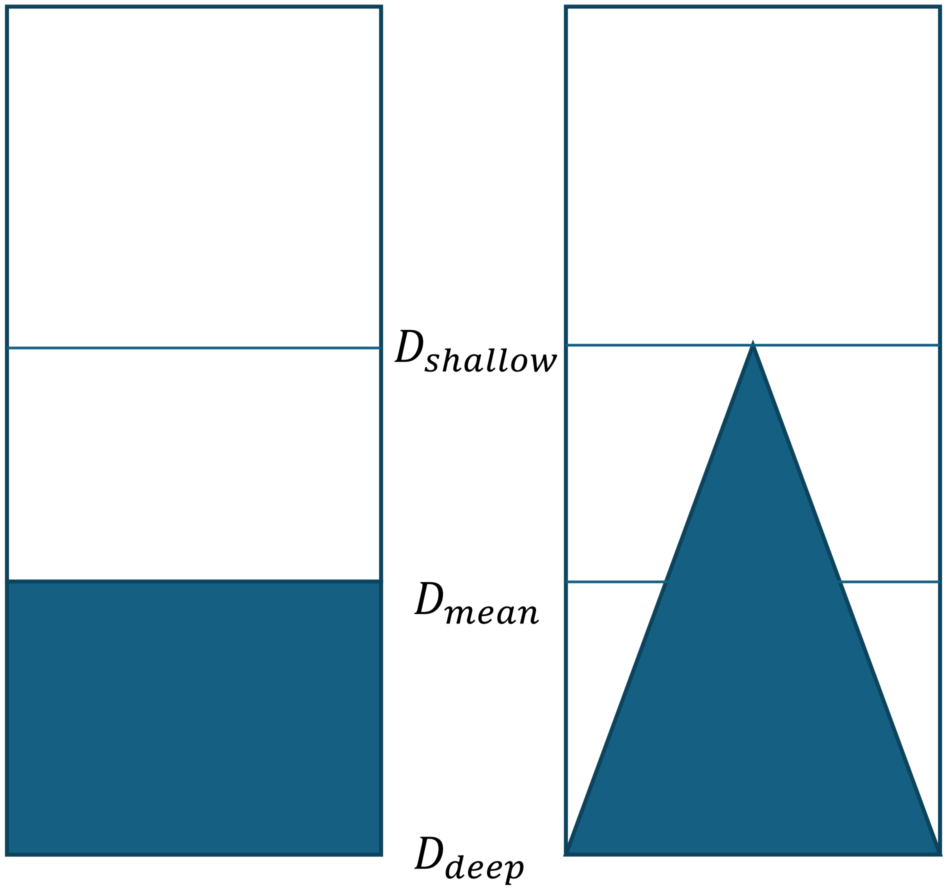
Global barotropic tides in MOM6 (Wang et al. (2024))



- Lower resolution porous barriers constructed from 0.04°
- Porous barriers significantly reduce tidal errors with the coarsened resolutions.

Adjusting cell centers: “porous media”

- Implementation: modify layer thickness
  - Solve $\eta_k^{(n)}$ from $h^{(n)} = \int_{\eta_{k+1}^{(n)}}^{\eta_k^{(n)}} w(z)dz$
  - Not affecting fully submerged grid cells in one-layer
  - Wetting and drying
  - Multi-layers



Applications to the Great Lakes

Represent narrow rivers with porous barriers and porous media

- Alleviate structured grid's resolution constraint
  - may also help unstructured grid
- Realistic channel width at both regional and climate model resolution
- Can have V-shaped channel profile if desired

Niagara River on 1km x 1km grid cells

Hydraulic control

- Hydraulic jump: rapid transition from supercritical (Fr>1) to subcritical (Fr<1)
  - Great energy loss, extremely turbulent

- Critical section Fr=1

- For supercritical flow, discharge is determined by upstream reservoir depth.
  - Simple relationship: $Q_c = \left(\frac{2}{3}\right)^{\frac{3}{2}} w_s g^{\frac{1}{2}} \Delta z^{\frac{3}{2}}$

Representing hydraulic control in MOM6

- Barotropic momentum equation:
  - $u'^{(n+1)} = \Delta t \cdot (u^{(n)} + F)$, where F is the summation of all momentum forcings.

- A critical velocity: $u_c \propto \alpha\sqrt{Q_c g}$, α is a tuning parameter.

- Hydraulic control:
  - $u^{(n+1)} = \min\left(u'^{(n+1)}, u_c\right)$ [assuming $u > 0$]

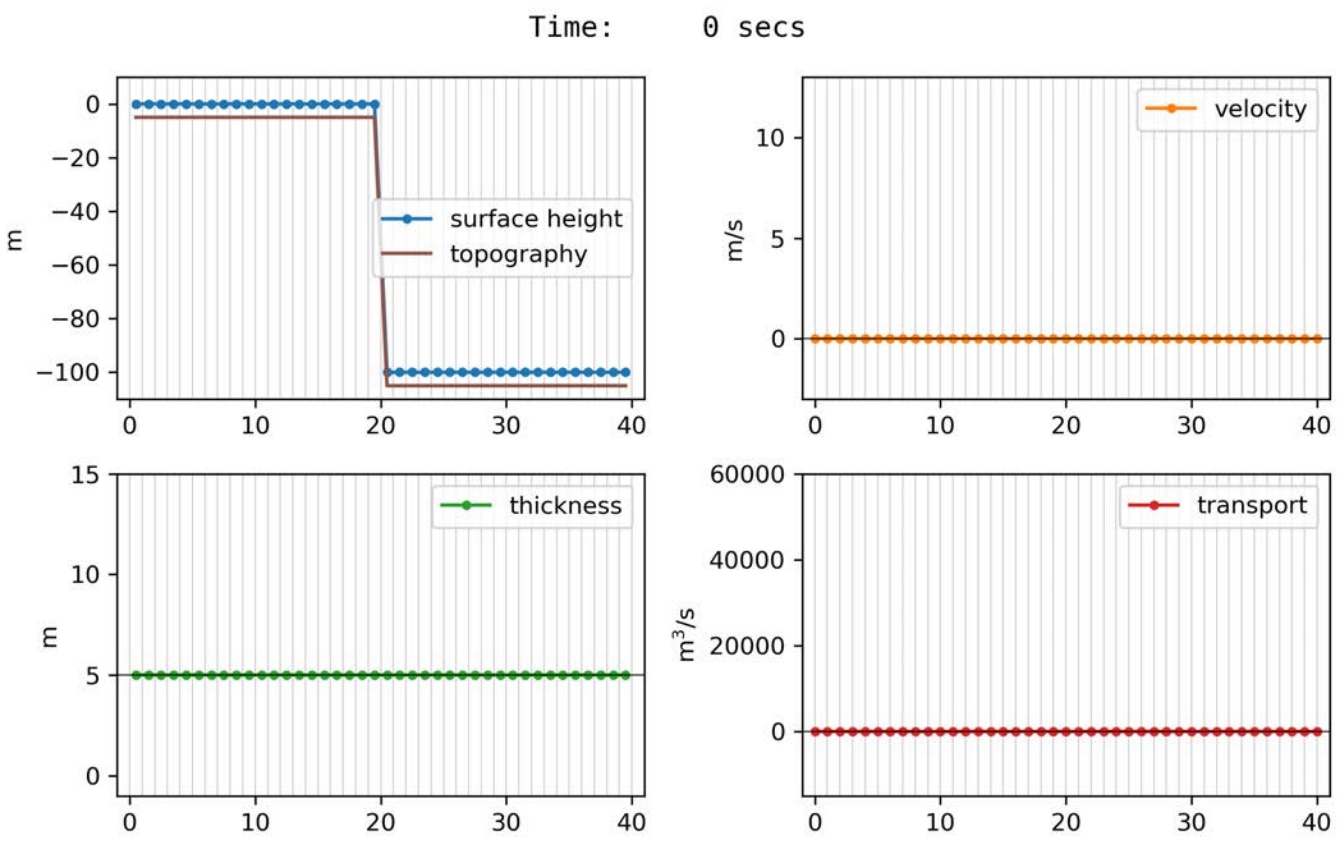
- An additional forcing term F_{hc}
  - $u^{(n+1)} = \Delta t \cdot \left(u^{(n)} + F + F_{hc}\right)$, where $F_{hc} = \min[\Delta t \cdot (u^{(n)} - u_c + F), 0]$

Some preliminary tests

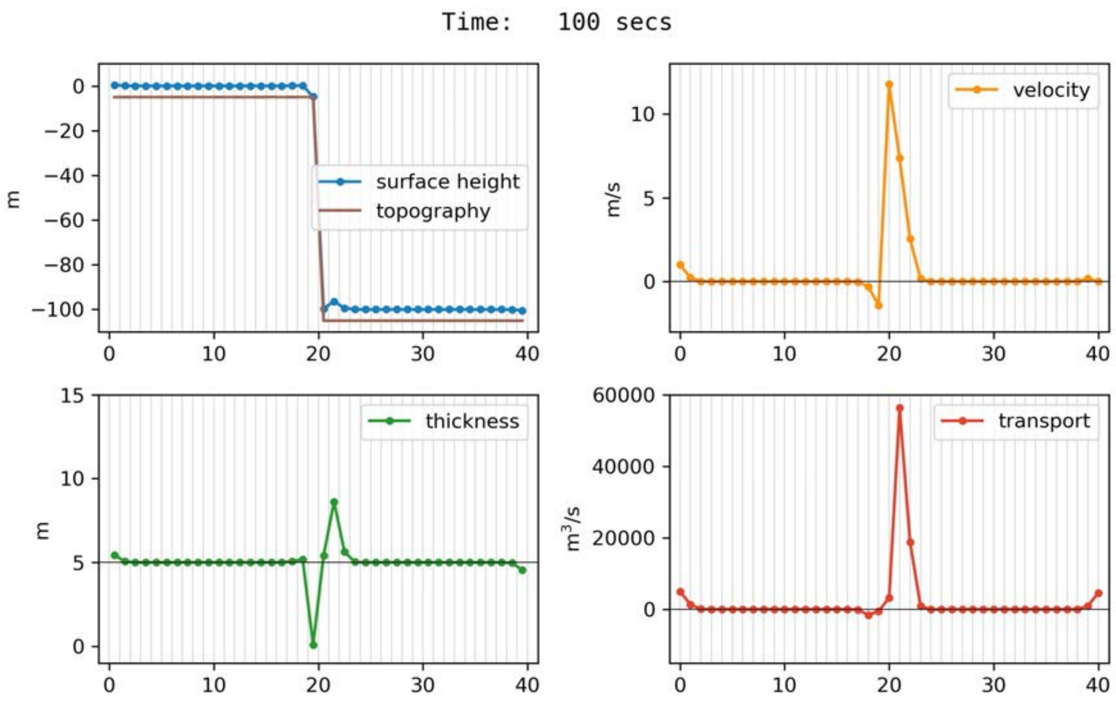
- Two-dimensional barotropic flow

- Specified inflow ($5000\ m^3/s$) at the left end
- Radiative OBC at the right end

- Grid size = 1 km
- Time step size = 10 s



Some preliminary tests



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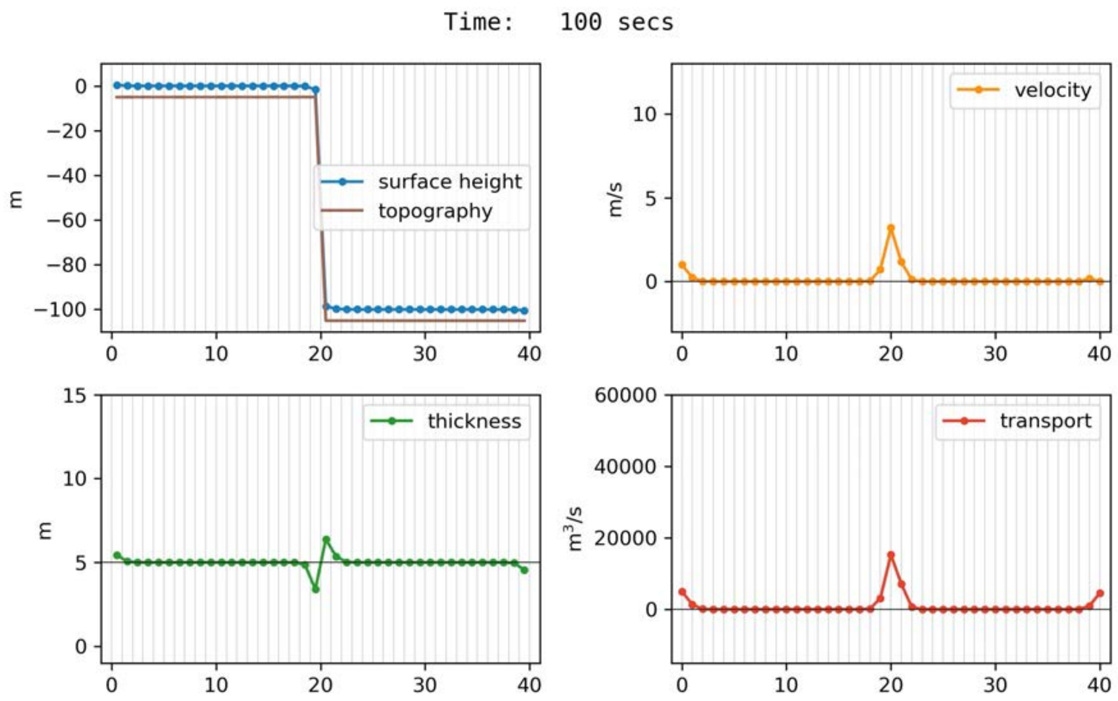

with hydraulic control term

Summary

- We plan to use MOM6 to simulate the Great Lakes, aiming for a dynamical and interactive component of a global ocean model and/or earth system model.
- Connecting the Great Lakes and maintaining the water levels is a major challenge.
- Sub-grid scale topography can help represent the narrow passages between lakes and also alleviates the shortcomings of coarse topography at global ocean model resolution.
- A prototype of hydraulic control representation is implemented in MOM6, which can help simulate rapids and waterfalls.